



# Proceedings of the 38th International Symposium on Automation and Robotics in Construction

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# Proceedings of the 38th International Symposium on Automation and Robotics in Construction

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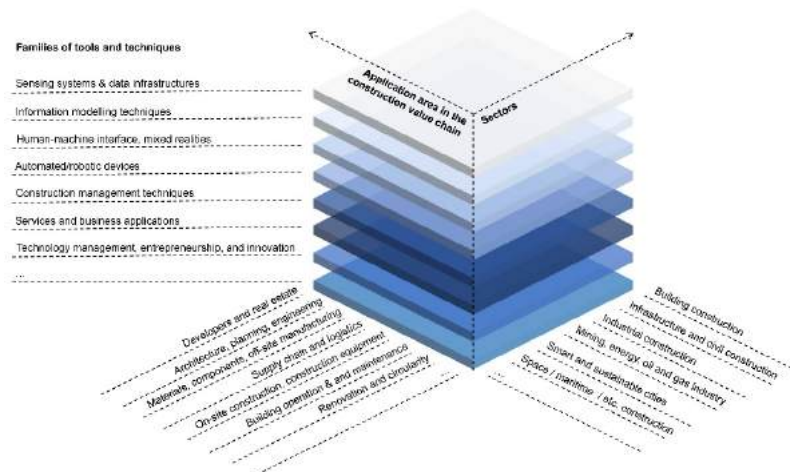
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# Foreword

ISARC is the premiere global conference in the domain of automation and robotics in construction. Specifically, ISARC 2021 is situated in an extremely interesting and important time in history: interest in digitising, automating, and robotising construction is rising in an unprecedented scale on a global level and cross all actors. This manifests itself in an increase in academic research activity, joint industry-academia collaboration projects, the emergence of strong start-ups, and a strong and growing interest of large, established organisations (contractors, machine/robot builders, governments etc.).

To prepare ISARC for the future, this year a first attempt was made to restructure IAARC's topic framework. The technical areas summarize the paper topic areas of interest, which represents all the research themes that are relevant to ISARC/IAARC. This is an important mechanism for the technical committee to consolidate the knowledge accumulated from each year's conference while allowing for the smooth incorporation of new research topics and trends in the community.



We hope that ISARC 2021 and the proceedings serves the audience and readers and all actors interested in automation and robotics in construction as a navigation and reference system for the domain and its most recent outputs and innovations.

Chen Feng, Thomas Linner, Ioannis Brilakis

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# A Proof of Concept Application of Sensing Technologies for Managing Proximity Hazards on Construction Sites

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## Abstract –

Construction is among the most dangerous industries for the safety of workers. Due to the dynamism typical of construction sites, where workers, materials and equipment resources are often in motion, collisions and contact with moving construction machineries and heavy equipment represents one of the main safety problems. The study described in this paper concerns with the preliminary development of a proximity warning system (PWS) for construction activities, which is based on the implementation of sensing technologies for situation awareness. Preliminary results, the feasibility of the PWS and its practical potential are described, highlighting the needs of a continuous monitoring process and the expectations about the system configuration. The adoption of the Ultra Wide Band (UWB) technology is within the scope of the paper. A front-end loader and an excavator are the construction machineries taken into account for the analysis of the use case, which considers the differences between equipment with fixed and variable geometries in terms of sensor devices. The possibilities for real-time position tracking of workers and equipment in both outdoor and indoor conditions based on the system architecture settings are discussed. Moreover, the compliance of the system architecture with the requirements imposed by the General Data Protection Regulation (GDPR) is described. Future works will validate the system in the context of actual construction sites. Furthermore, factors to be considered when sensing technologies for tracking the position of resources on construction sites are implemented will be evaluated as far as planning and scheduling activities are concerned.

## Keywords –

Construction safety; Proximity hazards; sensing technologies; Ultra Wide Band; General Data Protection Regulation

## 1 Introduction

Construction represents one of the most dangerous production sectors in terms of risks for the safety of workers [1]. In fact, although around 7% of the workforce worldwide is employed in construction, this accounts for between 30% and 40% of deaths at work [2].

Statistics compiled at international level show that construction safety is a global problem. In the United States, for example, census data from the U.S. Bureau of Labor Statistics (BLS) show that a total of 1.061 workers died in 2019 from fatal work injuries in the construction industry, accounting for 9.7% of all work-related fatalities; based on these data, construction ranks fourth among all manufacturing sectors for fatal work injuries [3]. As it emerges from the analysis of the data regularly provided by INAIL (Italian National Institute for Insurance against Accidents at Work) in relation to accidents in the workplace, construction has been always considered a high risk sector, with workers exposed to greater risks to their health and safety than in other work environments [4]. Although recording a slight decrease in 2018 compared to previous years, the Italian construction sector also shows the highest rate of accidents causing fatal injuries. In particular, looking at regional data, the accident phenomenon remains concentrated in northern Italy (60%), where Lombardy and Emilia Romagna alone account for about a third of all accidents (17% and 12% respectively). With regard to the construction sector, albeit with slightly decreasing numbers, in 2018 Lombardy was the region with the most complaints for accidents at work, 1389, followed by Veneto with 1060 (-23.7% complaints compared to Lombardy) and Emilia-Romagna with 982 complaints (-29.3% compared to Lombardy) [4].

### 1.1 Collision accidents with construction machineries in motion

In this context, proximity of workers to moving

construction machineries and heavy equipment represents one of the main safety problems in construction. More than six hundred construction worker deaths in the United States between 2004 and 2006 were linked to collisions and contact with moving construction machineries and heavy equipment [5]. INAIL data sets also show that the risk for collision accidents on construction sites represents one of the most frequent causes of death [6]. The causes of this kind of accident could be sought in the dynamic features proper to construction site activities, where the involved resources, such as workers, materials and equipment, are often in motion in situations of excessive proximity on a construction site space that is often insufficient, at least temporarily, to guarantee the safe performance of operations.

Collision accidents, in fact, are often due to a poor analysis of spatial interferences during construction planning and workspace design [7] [8]. Moreover, a lack of knowledge of existing specific risk factors, which is aggravated in daily activities by the possible loss of concentration due to fatigue and repetitive tasks, and the fact that no real-time information is gathered during the incident are some of the main factor influencing collision detection on construction sites [5]. Furthermore, visibility for workers driving construction machineries is often reduced due to blind spots and it increases the probability of risk of workers being run over and invested [2]. In fact, procedural non compliances causing fatal injuries are often related to the non-verification of the absence of operators by the driver of the construction machinery and the positioning of workers in the manoeuvring area. Further issues are detected such as shortcomings in the safety devices of the construction machineries (e.g., rear-view mirrors, reversing horns) and inadequate signposting of pedestrian transit routes [6].

In order to prevent workers being undetected in blind spots or in too close proximity, a warning system is needed that will promptly alert workers and equipment operators [5].

## 1.2 Objective of the research project

The study aimed at the preliminary development of a Proximity Warning System (PWS) for the real-time detection of a potential risk for construction workers because of an excessive proximity to a construction machinery in motion. Such a system has been conceived and developed in the form of a Proof of Concept (PoC) in order to demonstrate, as a preliminary result, its feasibility and practical potential, highlighting the needs of a continuous monitoring process and the expectations of the system configuration.

In particular, sensing technologies are considered in an Internet of Things (IoT) scenario that would allow

collecting real-time data directly from the construction site in order to support workers and protect their safety at work, taking into account the balance between safety and productivity. Moreover, the evaluation of the adoption of Ultra Wide Band (UWB) technology as a continuous monitoring system for the safety of construction workers is within the scope of the paper. UWB technology, in fact, has an optimal trade-off between location accuracy and cost of devices, which makes it the ideal solution for sensing precisely the distance in construction sites. Moreover, the design of a precise location service for the PWS should take into consideration workplace privacy, an aspect generally neglected by similar solutions proposed in literature.

In the following paragraphs the study will be introduced with respect to the research background. The research methodology implemented and the system architecture adopted for the development of the proximity warning system will be then described. Furthermore, the compliance of the proximity warning system with the requirements imposed by the General Data Protection Regulation (GDPR) will be shown. Finally, achieved results, findings and outcomes will be discussed in the light of the objectives of the research work, highlighting its limits with respect to the application domain. Possible future developments will be presented in terms of both the use case and the technological system.

## 2 Research background

Although accident prevention is a key step in the management of construction safety, traditional methods such as risk analysis, training of workers, site inspections and compilation of checklists, do not always guarantee optimal levels of continuous safety monitoring and effective and timely prevention of accidents during the construction process. Even when all the aforementioned measures are adopted effectively, workers tend not to recognise as a potential source of risk many of the hazards occurring on the construction site during their own activities [9] [10]; among them, there are the proximity of workers to construction machineries in motion [11].

### 2.1 Sensors technologies for situation and context awareness on construction sites

Strengthening the increasing attention to this type of risk for the safety of workers in the construction sector, the adoption of tracking systems to monitor construction entities (e.g., machineries, workers and materials) is discussed in literature. Vision-based and sensor-based methods exist for this purpose. The former track construction machineries from videos by deploying

cameras on construction sites. The latter refer to tracking entities by various sensors such as GPS, RFID, UWB, and laser scanners [12].

Cameras have become standard equipment on construction sites [12]. However, if currently no vision-based tracking method can achieve processing speed in the tracking of construction machines, especially in the case of multiple ones simultaneously, sensor-based methods for proximity warning systems allows the real-time tracking of construction entities [12]. Moreover, vision systems are also very sensitive to operating conditions (e.g., reduced visibility due to dust on the construction site, or rain) and they require much more maintenance (e.g., frequent cleaning of the system optics). Furthermore, vision-based methods could be more expensive of sensor-based ones (e.g., UWB) and many more cameras are needed to avoid blind spots on the construction site.

Among the sensor-based methods, the use of Inertial Measurement Units (IMU) capable of tracking the kinetic movement data of workers to determine the areas where falls are most likely to occur has been exploited. Other studies have relied on the adoption of Unmanned Aerial Systems (UAS) to identify situations of risk of falling from heights. The increasing use of wearable devices also got the potential to make workers significantly safer on construction sites [13]. The adoption of sensor-based methods has often been referred to proximity warning systems. PWS locate the position of workers in relation to potential safety hazards in the workplace such as proximity to restricted areas and construction machineries in motion. In addition, proximity warning systems use localisation systems not only to monitor the relative position of workers in relation to possible hazards, but also to warn them, by sending notification signals, if they come dangerously close to sources of risk to their safety. Previous studies have shown that the adoption of sensors systems can effectively improve the perception of risks by workers, who are able to take appropriate measures to avoid them once they receive an alert signal [11].

Considering wearable sensor devices, previous studies have used Bluetooth-based Low-Energy (BLE) technology [14] in order to identify the positions of workers with respect to potentially dangerous situations; other attempts, instead, have adopted a real-time localisation system (RTLS) based on Radio-frequency identification (RFID) technology [15] to locate workers and equipment with respect to the position of high-risk or restricted areas, implementing radio-frequency sensing technology also in order to identify possible collisions between workers, heavy equipment and moving construction machineries [5]. Several other technologies, including laser scanning, UWB, Global Positioning System (GPS), and computer vision have been suggested

for similar purposes [11].

## 2.2 UWB technology

The adoption of the UWB technology is of particular interest. It has been developed to transmit spectrum-dispersive modulated signals over very wide bands (i.e., 500 MHz or more) [16]. UWB applications, in fact, include sensor networks where high data rates are not required but it may be useful to ensure a good coverage range. They also include remote tag localisation systems for applications such as logistics, safety, medical, domestic, security and military.

A typical UWB RTLS is shown in Figure 1. An infrastructure of nodes called *anchors* is deployed in fixed locations while nodes called *tags* are applied to the mobile objects which should be tracked. The network coordinator is the node in charge to allow new nodes to join the network as well as to organise the transmission timing among nodes.

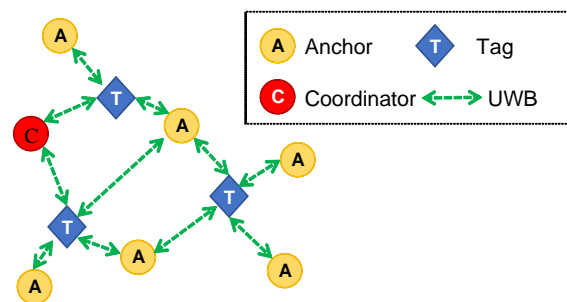


Figure 1 UWB RTLS principle architecture

Usually deployed with a maximum distance of 25 m, anchors send radio pulses to start the location process, which usually has an error within 30 cm with an update rate every 50 ms, depending on the available hardware. Such a result, it is hard to obtain using GPS technology, unless to adopt solution like GPS receivers with Real Time Kinematic (RTK) support, but which costs are not feasible for a large deployment in construction sites. Usually deployed for automatic asset tracking in indoor environments, UWB technology has several benefits that satisfy large part of the use case requirements. UWB is capable of reaching a range of 100 m in outdoor environments. It also does not need additional hardware to operate, such as routers. Generally, dynamic scenarios (i.e., with moving objects) such as construction sites can be monitored adopting UWB sensor technologies, but there may be problems if the environment in which the monitoring is done undergoes major changes that prevent, for example, the reception of signals. Moreover, this technology requires manual anchor localisation and registration in RTLS system for tag trilateration. In the literature there are several solutions to address this issue, by using self-configuration approaches, but, the

complexity, in term of protocol effort, introduced by them is not justified by the considered use case.

### 3 Research methodology

UWB technology was selected for the development of the PWS. Research activities were managed in six macro-phases, with some of them overlapping during the testing in order to proceed with an iterative process of data collection and analysis (Figure 2).

- Phase 1 - analysis of the use case for the applicability of the PWS in construction site safety management
- Phase 2 – set up of the system architecture
- Phase 3 - on-site tests for real-time proximity analysis
- Phase 4 - iterative review of the system architecture
- Phase 5 - Verification of the compliance with GDPR

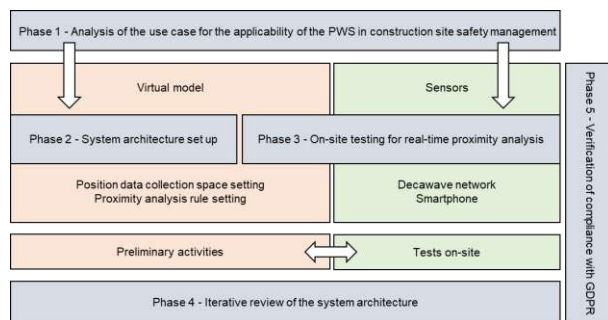


Figure 2 – Research methodology

#### 3.1 Description of the use case

The paper analyses the specific use case related to the risk of a construction worker of being run over or invested by a construction machinery in motion. For the purpose of the study, two construction machineries were considered, chosen because of their different configurations: (1) fixed geometry (i.e., the body of the construction machinery has a fixed geometry and configuration during movement) and (2) variable geometry (i.e., the body of the construction machinery has a variable configuration during movement):

1. front-end loader [Takeuchi TL6R] (i.e., fixed geometry) (Figure 3)
2. excavator [Takeuchi TB640] (i.e., variable geometry) (Figure 4) (Figure 5)

Based on technical documentation and workforce experience, five circular areas around the construction machineries have been defined:

1. *black area* (i.e., the radius of action of the

2. *red area* (i.e., an area of 2 m from the radius of action of the construction machinery in which, according to the manufacturer's instructions, no persons may be present when the equipment is in motion) within which an immediate reaction is needed to avoid permanent injuries or death;
3. *yellow area*, within which operations are allowed but attention must be made as the risk could quickly increase to red and black;
4. *green area*, within which the presence of heavy machinery working nearby is notified;
5. *white area*, within which no risk related to heavy machinery operations is present.



Figure 3 Front-end loader (fixed geometry)



Figure 4 Excavator (variable geometry) – retracted arm



Figure 5 Excavator (variable geometry) – extended arm

### 3.2 System architecture setup

The system architecture setup is shown in Figure 6 and it is composed by three layers: infrastructure, operator and construction machinery.

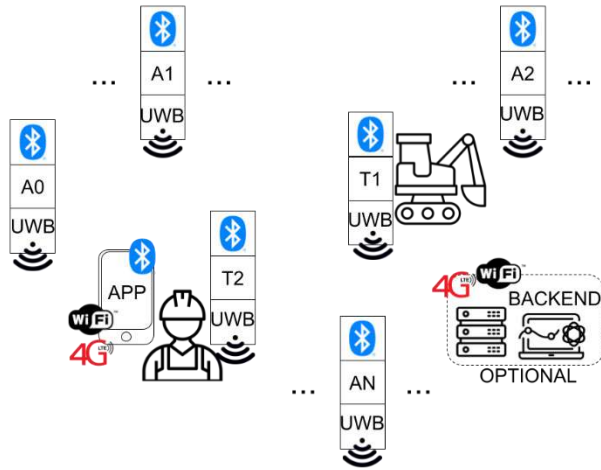


Figure 6 The architecture of UWB position detection system

The infrastructure layer is composed by a network of Decawave DWM1001, which can act as both anchors or tags with a suitable configuration (marked as AX for anchors and TX for tags in Figure 6). Tags are connected to a smartphone, running a custom APP developed for the project, by a Bluetooth Low Energy (BLE) link. The positions of tags are, then, locally collected by the smartphone that could perform the calculations needed to identify the area and alert the operator. If a suitable communication infrastructure (e.g., Wi-Fi or LTE) is available, the smartphone could act as a gateway and forward position data via MQTT (Message Queue Telemetry Transport) to a cloud backend in charge of all the computation. The performance difference between a full cloud or a mixed cloud-edge architecture has been analysed in [17][18].

### 3.3 PWS compliance with the General Data Protection Regulation (GDPR) for data privacy

The development of PWS has raised questions about the risk of violation of the privacy of workers' data due to the continuous monitoring of their position on the construction site to ensure the effective development of an alert system. In this sense, it is underlined that the absolute position of workers is never recorded, while their relative position with respect to a moving construction machinery is recorded: this allows to monitor their exposure to the risk and not their actual location on the construction site.

In addition, each operator has access to data related only to the tags and UWB anchors assigned to a specific worksite. The tag-user association is recorded in the app the PWS is based on and is not exported to other systems; it is also assumed that this association activity is validated by the site manager (e.g., during the delivery of personal protective equipment).

Moreover, each app has a client with a unique ID, which is generated each time the user accesses a specific part of the app. The data saved involves only the tag information regarding the location of the resources and their mutual positioning; if necessary, it is possible to add, as additional data, which client actually sent this location. The tag-media association follows the same logic.

The only information known to all members of the system, therefore, is the type of tag (user/worker, construction machinery) or UWB (which delimits the monitored worksite area). Based on those considerations, the PWS complies, in this preliminary setting, with the European General Data Protection Regulation (GDPR) in terms of data privacy.

## 4 Results of the application of sensors technology

Figure 7 shows the experimental setup. It is formed by 5 anchors (A, B, C, D, E) and a network coordinator I. The area is divided in two part: an *indoor area* on the left of anchor B and E, and an *outdoor area* on the right of anchors B and E. B and E are positioned in the indoor side of a concrete wall with a 2 m open door in the middle (pink line in Figure 7). The experimental set-up has been defined in order to validate the behaviour of UWB sensors in significant operational environments (indoor as well as outdoor).

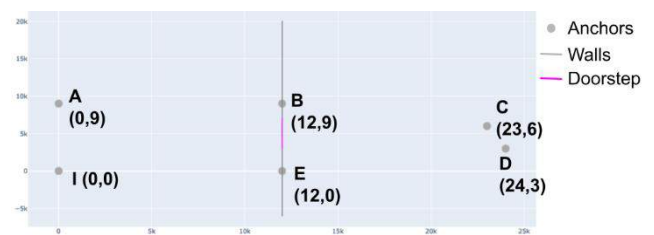


Figure 7 UWB test setup

Data have been collected using the MQTT+ backend configuration leveraging an ad-hoc Wi-Fi network to connect the smartphone with a laptop PC acting as backend. Since the type of movement of the workers and of the construction machinery are different, two set of experiments have been performed, to validate the capability of the UWB technology to monitor each of them independently:

1. detection of an operator equipped with a tag on his chest, as shown in Figure 8 (top);

2. detection of a moving construction machinery as described in Section 3.1. For the variable geometry of the excavator (i.e., retracted arm and extended arm) two tags have been installed as shown in Figure 8.

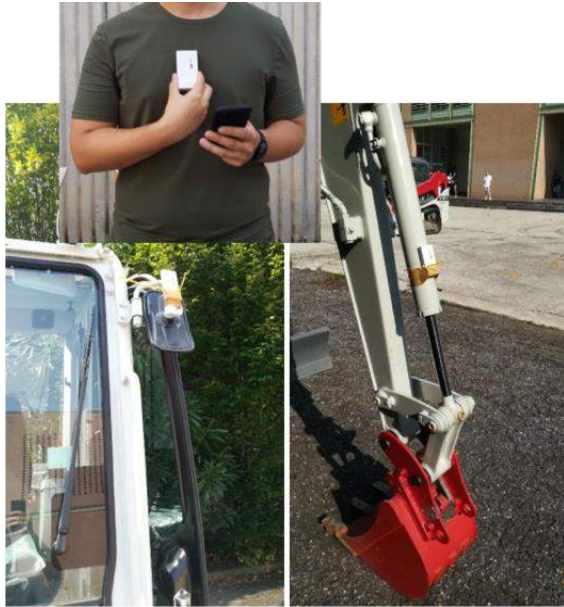


Figure 8 Position of tags for both operator and construction machinery

Figure 9 and Figure 10 show, respectively, the results of the experiments performed during the first and the second set of experiments. In particular, Figure 9 shows the real-time position of a worker walking alone outside and then going inside the building. Figure 10 shows the position of a moving construction machinery, in the same area, without the presence of the worker. The construction machinery started moving in the indoor area. In both the experiments, the position of the workers and of the construction machinery has been sampled each 50 ms.

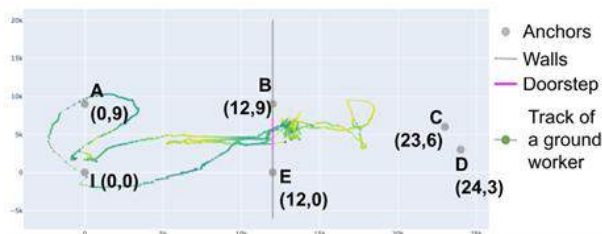


Figure 9 Position tracking of a worker

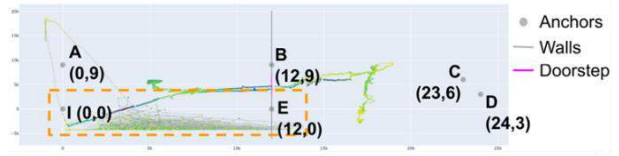


Figure 10 Position tracking of a machinery

Thanks to the location accuracy provided by the UWB sensors (nominal location accuracy of 30 cm), the proposed PWS is able to detect the fine details of the movement of the construction machinery. This is the reason of the overlapping trajectories shown in the slashed orange rectangle, which correspond to the operation of the construction machinery.

## 5 Conclusions

### 5.1 Discussion of the results

The obtained results aim to demonstrate the applicability of the proposed system in a near to reality testing environment, which includes the presence of workers as well as construction machinery. As demonstrated by the experimental results, the system is able to track the real-time movement of both a worker as well as of a construction machinery, in indoor as well as outdoor scenarios. With the respect to similar proximity warning solutions used in construction sector based on Bluetooth technology [19] [20] [21] [22], ultrasonic [23] or LoRaWAN devices [24], the proposed solution exploits the use of UWB radio to reach a localization accuracy on the order of 30 cm, at an update rate up to 50 ms, as indicate by the technology provider [25] and by scientific literature **Error! Reference source not found.**

According to the technology provider documentation [25], there are several factors affecting the localization accuracy. One of the main sources of uncertainty is the power of the received signal, which is affected by the environmental conditions. The UWB technology is only partially affected by multipath effect, because the UWB pulses are transmitted in the RF frequency between 3.5 GHz and 6.5 GHz. This frequency band is rather immune to multipath effect, but it could experience the radio frequency attenuation of the signal. According to the device technical document [25], an attenuation of the signal varying in the range from -60 dbm to -95 dbm, corresponds to an error in the location estimation from -20 cm to 10 cm, respectively.

Notwithstanding these limitations, the UWB remains the most feasible solution for a precise location at a low cost. As demonstrated in the paper, the system is able to track, at the same time, the position of operators and of machineries in the area under monitoring. In fact, when the geometrical distance between a worker and each of

the construction machineries located in the site is below one of the security areas defined in Section 3.1, an alert or a warning (depending the security area involved) is raised to the involved operator. The location accuracy provided by UWB devices was taken into account when defining the security areas, to avoid any risks for the workers.

In addition, according to the recent trends in proximity warning system, which achieved some success as a result of contact tracing systems [26], the proposed solution has been designed to take into account the privacy of the workers, as highlighted in Section 3.3.

## 5.2 Limitations of the study

First of all, the tests described in this paper were carried out in a simplified environment and considering separately the movement and the related real-time detection of the resources "workers" and "equipment" (i.e., construction machineries). In fact, the tests do not fully consider the complexities linked to the dynamism of a construction site.

As regards the technologies adopted, which have been selected for their easy availability on the market and low cost that has enabled them to be used effectively within the time and economic resources of this project, the problem of antenna direction and orientation of UWB tags and anchors to ensure continuous signal transmission regardless of the positioning and movement of the resources has not yet been resolved.

A further limitation of this project is that, to date, no indications have been given as to the actual distances to be maintained between the operator and the moving construction machinery in order to successfully guarantee the safety of workers in the event of the risk of being run over or hit by moving construction machineries. These analyses are in the development phase and need to take into account all the aspects related to the quality of the data as well as the time needed for its recording, processing and subsequent communication in the PWS.

## 5.3 Future works

Future works will validate the measurement system in the context of actual construction sites, with a focus on a panel of construction activities that requires collaboration between workers and construction machineries (e.g., procedure of excavation).

Moreover, a further series of tests will be carried out that integrate the system architecture with certified telemetry systems in order to set it up a correct monitoring process and assess the effective validity of the digital twin represented in the virtual environment.

A suitable notification system will be set up in order to communicate the presence of a safety risk to the workers, once the PWS detects excessive proximity

between workers and moving construction machineries. These notification systems will have to consider the conditions of disturbance and noise typical of construction sites as well as the risk of a decrease in the attention of operators in the event of receiving excessive notifications.

Furthermore, in order to optimise the PWS in terms of technological equipment, a collaboration with manufacturers could allow acting directly on the construction machinery itself, hypothesising scenarios of gradual slowing down and stopping in the event of danger or sending timely notifications and warning signals directly from the equipment itself.

Finally, from the construction management perspective, future developments could also integrate the assessment of the positioning of UWB anchors in the design of construction site layouts and the planning of construction phases so as to include their installation and possible displacement among the activities to be taken into account in order to ensure signal coverage that is always consistent with the activities currently underway.

Generally speaking, the current and expected outcomes show how the proposed and tested technical solutions could be exploited with a broader digital ecosystem, enabling a data-driven control room for safety management.

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